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Production of jets at forward rapidities in hadronic collisions

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Summary. — We discuss high-p_T production processes at forward rapidities in hadron-hadron collisions, and describe recent results from using QCD high-energy factorization in forward jet production at the LHC.

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1. – Introduction

Experiments at the Large Hadron Collider (LHC) will explore the region of large rapidities both with general-purpose detectors and with dedicated instrumentation, including forward calorimeters and proton taggers [1, 2, 3, 4, 5, 6, 7]. The LHC forward-physics program involves a wide range of topics, from new particle discovery processes [3, 8, 9] to new aspects of strong interaction physics [7, 10] to heavy-ion collisions [11, 12]. Owing to the large center-of-mass energy and the unprecedented experimental coverage at large rapidities, it becomes possible for the first time to investigate the forward region with high-$p_\perp$ probes.

In this article we report on studies of forward production of jets [13] based on QCD high-energy factorization at fixed transverse momentum [14]. This theoretical framework serves to take into account consistently both the higher-order logarithmic corrections in the large rapidity interval and those in the hard jet transverse energy. In Sec. 2 we introduce the basic structure of jet production in the LHC forward region. In Sec. 3 we consider associated parton showering effects. In Sec. 4 we consider effects from the short-distance matrix elements that control the resummation of logarithmically enhanced corrections in $\sqrt{s}/E_T$, where E_T is the hard jet transverse energy. We give concluding remarks in Sec. 5.

2. – Forward jets at the LHC

The hadroproduction of a forward jet associated with hard final state X is pictured in Fig. 1. The kinematics of the process is characterized by the large ratio of sub-energies $s_2/s_1 \gg 1$ and highly asymmetric longitudinal momenta in the partonic initial state, $q_A \cdot p_B \gg q_B \cdot p_A$. At the LHC the use of forward calorimeters allows one to measure

events where jet transverse momenta $p_\perp > 20$ GeV are produced several units of rapidity apart, $\Delta y \gtrsim 4 \div 6$ [1, 5, 7]. Working at polar angles that are small but sufficiently far from the beam axis not to be affected by beam remnants, one measures azimuthal plane correlations between high-$p_\perp$ events (Fig. 2) widely separated in rapidity [7, 13].

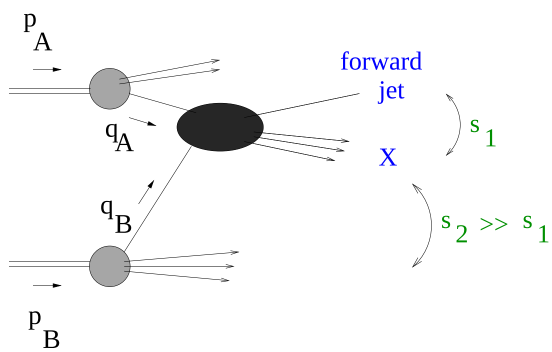

Fig. 1. – Jet production in the forward rapidity region in hadron-hadron collisions.

The presence of multiple large-momentum scales implies that, as recognized in [15, 16, 17], reliable theoretical predictions for forward jets can only be obtained after summing logarithmic QCD corrections at high energy to all orders in α_s(1). This motivates efforts [22, 23, 24, 25] to construct new, improved algorithms for Monte Carlo event generators capable of describing jet production beyond the central rapidity region.

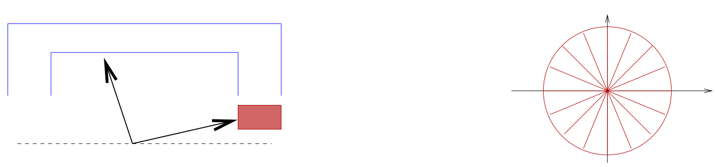

Fig. 2. – (Left) High-$p_\perp$ events in the forward and central detectors; (right) azimuthal plane segmentation.

In the LHC forward kinematics, realistic phenomenology of hadronic jet final states requires taking account of both logarithms of the large rapidity interval (of high-energy type) and logarithms of the hard transverse momentum (of collinear type). The theoretical framework to resum consistently both kinds of logarithmic corrections in QCD calculations is based on high-energy factorization at fixed transverse momentum [14].

Ref. [13] investigates forward jets in this framework. It presents the short-distance

(1) Analogous observation applies to forward jets associated to deeply inelastic scattering [18, 19]. Indeed, measurements of forward jet cross sections at Hera [20] have illustrated that either fixed-order next-to-leading calculations or standard shower Monte Carlos [20, 21, 22], e.g. Pythia or Herwig, are not able to describe forward jet *ep* data.

matrix elements needed to evaluate the factorization formula, including all partonic channels, in a fully exclusive form. On one hand, once convoluted with the BFKL off-shell gluon Green's function according to the method of [14], these matrix elements control the summation of high-energy logarithmic corrections to the jet cross sections. They contain contributions both to the next-to-leading-order BFKL kernel [26] and to the jet impact factors [27, 28]. On the other hand, they can be used in a shower Monte Carlo generator implementing parton-branching kernels at unintegrated level (see e.g. [29, 30] for recent works) to generate fully exclusive events.

The high-energy factorized form [13, 14, 27] of the forward-jet cross section is represented in Fig. 3a. Initial-state parton configurations contributing to forward production are asymmetric, with the parton in the top subgraph being probed near the mass shell and large x, while the parton in the bottom subgraph is off-shell and small-x. The jet cross section differential in the final-state transverse momentum $Q_\perp$ and azimuthal angle φ is given schematically by [13, 14, 27]

$$\frac{d\sigma}{dQ_\perp^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\widehat{\sigma}}{dQ_\perp^2 d\varphi} \otimes \phi_{g^*/B} \quad , \tag{1}$$

where $\otimes$ specifies a convolution in both longitudinal and transverse momenta, $\widehat{\sigma}$ is the hard scattering cross section, calculable from a suitable off-shell continuation of perturbative matrix elements, $\phi_{a/A}$ is the distribution of parton a in hadron A obtained from near-collinear shower evolution, and $\phi_{g^*/B}$ is the gluon unintegrated distribution in hadron B obtained from non-collinear, transverse momentum dependent shower evolution.

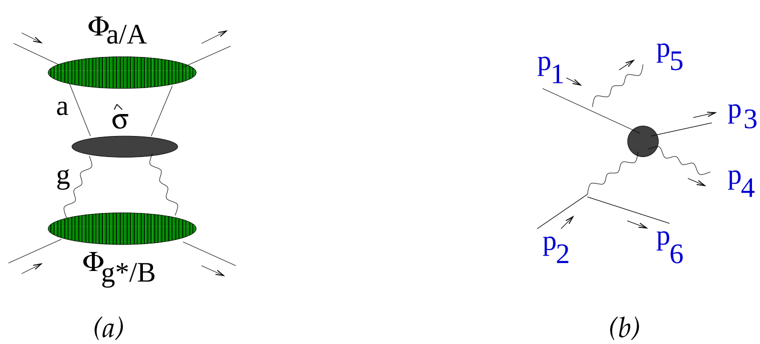

Fig. 3. – (a) Factorized structure of the cross section; (b) a typical contribution to the qg channel matrix element.

In the next section we comment on the initial-state shower evolution. In Sec. 4 we turn to hard-scattering contributions.

3. – Parton shower evolution

Parton distributions can be obtained by parton-shower Monte Carlo methods via branching algorithms based on collinear evolution of the jets developing from the hard event [31]. The branching probability can be given in terms of two basic quantities (Fig. 4), the splitting functions at the vertices of the parton cascade and the form factors

to go from one vertex to the other. An important ingredient of this approach is the inclusion of soft-gluon coherence effects [31, 32, 33] through angular ordering of the emissions in the shower.

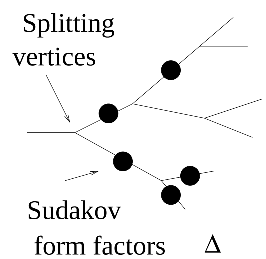

Fig. 4. – Parton branching in terms of splitting probabilities and form factors.

Corrections to collinear-ordered showers, however, arise in high-energy processes with multiple hard scales [7, 34, 35], as is the case with the production of jets at forward rapidities in Fig. 1. In particular, new color-coherence effects set in in this regime due to emissions from internal lines in the branching decay chain [7, 27, 36] that involve space-like partons carrying small longitudinal momentum fractions. The picture of the coherent branching is modified in this case because the emission currents become dependent on the total transverse momentum transmitted down the initial-state parton decay chain [14, 27, 34, 35, 37]. Correspondingly, one needs to work at the level of unintegrated splitting functions and partonic distributions [38, 39] in order to take into account color coherence not only for large x but also for small x in the angular region (Fig. 5)

$$\alpha/x > \alpha_1 > \alpha \quad , \tag{2}$$

where the angles α for the partons radiated from the initial-state shower are taken with respect to the initial beam jet direction, and increase with increasing off-shellness.

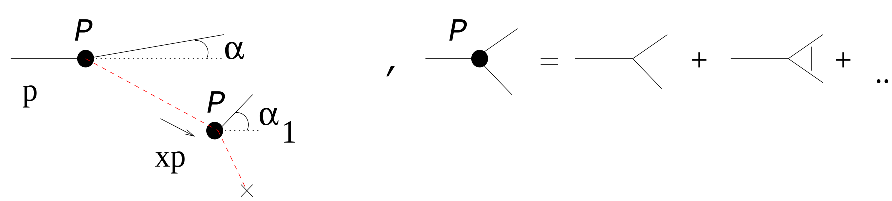

Fig. 5. – (left) Coherent radiation in the space-like parton shower for $x \ll 1$; (right) the unintegrated splitting function $\mathcal{P}$, including small-x virtual corrections.

The case of LHC forward jet production is a multiple-scale problem where coherence effects of the kind above enter, in the factorization formula (1), both the short-distance factor $\widehat{\sigma}$ and the long-distance factor ϕ. Contributions from the coherence region (2) are

potentially enhanced by terms $\alpha_s^n \ln^m \sqrt{s}/p_\perp$ where $\sqrt{s}$ is the total center-of-mass energy and $p_\perp$ is the jet transverse momentum(²). These contributions represent corrections to the angular ordering implemented in collinear showers and are not included at present in standard Monte Carlo generators [31]. Work to develop methods for unintegrated shower evolution, capable of including such corrections, is underway by several authors.

The proposal [29] incorporates NLO corrections to flavor non-singlet QCD evolution in an unintegrated-level Monte Carlo. The approach is based on the generalized ladder expansion of [41], which is extended to the high-energy region in [40]. This approach could in principle be applied generally, including flavor singlet evolution, and used to treat also forward hard processes.

Shower Monte Carlo generators based on small-x evolution equations, on the other hand, have typically included the unintegrated gluon distribution only [35, 37]. We observe that unintegrated quark contributions can be incorporated for sea quarks via the transverse-momentum dependent but universal splitting kernel given in [40], which has the structure

$$\mathcal{P}_{g\to q}(z; q_\perp, k_\perp) = P_{qg}^{(0)}(z) \left(1 + \sum_{n=1}^{\infty} b_n(z)(k_\perp^2/q_\perp^2)^n\right) \quad , \tag{3}$$

where $P^{(0)}$ is the DGLAP splitting function, and all coefficients b_n are known. The kernel (3) has been used for inclusive small-x calculations [42]. Its Monte Carlo implementation is relevant to take into account effects from the unintegrated quark distribution in the simulation of exclusive final states [43]. We note that quark contributions to evolution at the fully unintegrated level will also enter the treatment of the subleading high-energy corrections that are being discussed for jet production [28, 44].

Analyses of forward jet hadroproduction including parton showering effects are in progress [45].

4. – The factorizing hard cross sections

Logarithmic corrections for large rapidity $y \sim \ln s/p_\perp^2$ are resummed to all orders in α_s via Eq. (1), by convoluting (Fig. 3) unintegrated distribution functions with well-prescribed short-distance matrix elements, obtained from the high-energy limit of higher-order scattering amplitudes [13, 27]. With reference to Fig. 3b, in the forward production region we have $(p_4 + p_6)^2 \gg (p_3 + p_4)^2$ and longitudinal momentum ordering, so that

$$p_5 \simeq (1 - \xi_1)p_1 \quad , \quad p_6 \simeq (1 - \xi_2)p_2 - k_\perp \quad , \quad \xi_1 \gg \xi_2 \quad . \tag{4}$$

Here ξ_1 and ξ_2 are longitudinal momentum fractions, and $k_\perp$ is the di-jet transverse momentum in the laboratory frame. It is convenient to define the rapidity-weighted average $Q_\perp = (1 - \nu)p_{\perp 4} - \nu p_{\perp 3}$, with $\nu = (p_2 \cdot p_4)/p_2 \cdot (p_1 - p_5)$. In Fig. 3b Eq. (1) factorizes the high-energy qg amplitude in front of the (unintegrated) distribution from

(²) Terms with $m > n$ are known to drop out from inclusive processes due to strong cancellations associated with coherence, so that, for instance, the anomalous dimensions γ^{ij} for space-like evolution receive at most single-logarithmic corrections at high energy [26, 40]. This need not be the case for exclusive jet distributions, where such cancellations are not present and one may expect larger enhancements.

the splitting in the bottom subgraph. The factorization in terms of this parton splitting distribution is valid at large y not only in the collinear region but also in the large-angle emission region [14]. As a result the rapidity resummation is carried out consistently with perturbative high-$Q_\perp$ corrections [14, 27] at any fixed order in α_s.

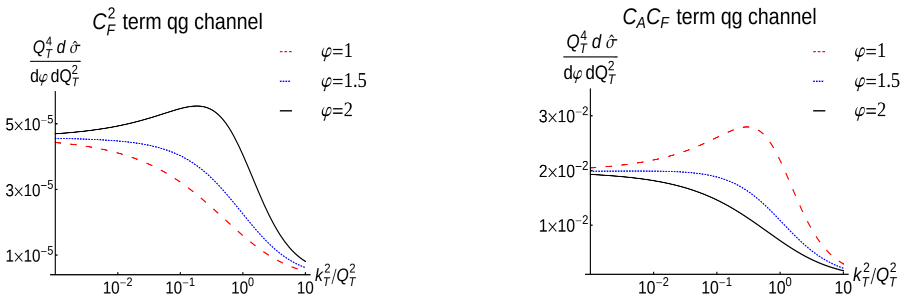

Fig. 6. – The k_T/Q_T dependence of the factorizing qg hard cross section at high energy [13]: (left) C_F^2 term; (right) $C_F C_A$ term.

The explicit expressions for the relevant high-energy amplitudes are given in [13]. Figs. 6 and 7 illustrate features of the factorizing matrix elements, partially integrated over final states. We plot distributions differential in $Q_\perp$ and azimuthal angle φ ($\cos\varphi = Q_\perp \cdot k_\perp / |Q_\perp||k_\perp|$) for the case of the qg channel. Fig. 6 shows the dependence on $k_\perp$, which measures the distribution of the third jet recoiling against the leading di-jet system. Fig. 7 shows the energy dependence.

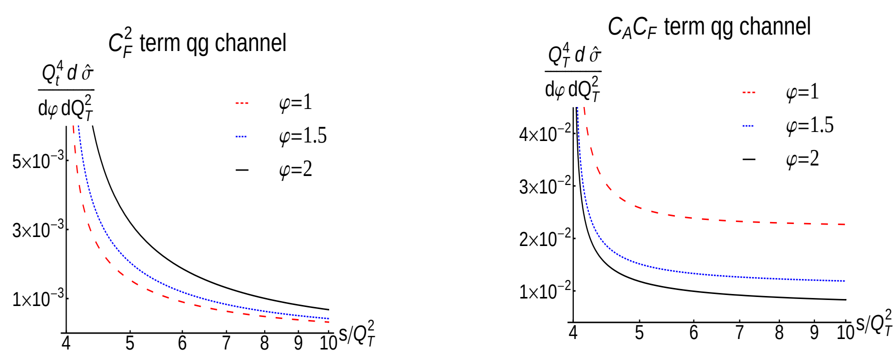

Fig. 7. – The energy dependence of the qg hard cross section [13] ($k_T/Q_T = 1$).

The region $k_\perp/Q_\perp \to 0$ in Fig. 6 corresponds to the leading-order process with two back-to-back jets. The resummation of the higher-order logarithmic corrections for large $y \sim \ln s/p_\perp^2$ is precisely determined [14, 27] by integrating the u-pdfs over the $k_\perp$-distribution in Fig. 6. So the results in Fig. 6 illustrate quantitatively the significance of contributions with $k_\perp \simeq Q_\perp$ in the large-y region. The role of coherence from multi-gluon emission is to set the dynamical cut-off at values of $k_\perp$ of order $Q_\perp$. Non-negligible effects arise at high energy from the finite-$k_\perp$ tail. These effects are not included in collinear-branching generators (and only partially in fixed-order perturbative calculations), and become more and more important as the jets are observed at large

rapidity separations. The dependence on the azimuthal angle in Figs. 6 and 7 is also relevant, as forward jet measurements will rely on azimuthal plane correlations between jets far apart in rapidity (Fig.2).

Results for all other partonic channels are given in [13]. After including parton showering [45], quark- and gluon-initiated contributions are of comparable size in the LHC forward kinematics: realistic phenomenology requires including all channels. Note also that since the forward kinematics selects asymmetric parton momentum fractions, effects due to the $x \to 1$ endpoint behavior [46] at the fully unintegrated level may become relevant as well.

Let us finally recall that if effects of high-density parton dynamics [10, 47] show up at the LHC, they will influence forward jet event distributions. In such a case, the unintegrated formalism discussed above would likely be the natural framework to implement this dynamics at parton-shower level.

5. – Conclusion

Forward + central detectors at the LHC allow jet correlations to be measured across rapidity intervals of several units, $\Delta y \gtrsim 4 \div 6$. Such multi-jet states can be relevant to new particle discovery processes as well as new aspects of standard model physics.

Existing sets of forward-jet data in ep collisions, much more limited than the potential LHC yield, indicate that neither conventional parton-showering Monte Carlos nor next-to-leading-order QCD calculations are capable of describing forward jet phenomenology. Improved methods to evaluate QCD predictions are needed to treat the multi-scale region implied by the forward kinematics.

In this article we have discussed ongoing progress, examining in particular factorization properties of multi-parton matrix elements in the forward region, and prospects to include parton-showering effects with gluon coherence not only in the collinear region but also in the large-angle emission region.

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